Designing a Bearing Test Bench for Water Lubricated Bearing Materials Applied to the Hydro Electric Industry.

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Abstract

Guide and thrust bearings are vital to the operation of hydroelectric turbines. Under ideal operating conditions these bearings utilize a hydrodynamic film with a low coefficient of friction and negligible wear rate. During start up and shut down of the unit, the hydrodynamic film fails, and the bearing material is subject to mixed and boundary lubrication. In this condition, pressure-velocity ratios (PV ratios) are used to evaluate the wear rate of a material at different loading conditions but must be obtained empirically. A survey of standards (ASTM, DNV, ISO, etc.) revealed that several different methods exist but do not accurately reflect the operating and transient conditions of a bearing. The critical parameters for bearing operation are: bearing surface speed, pressure, coefficient of friction, lubricant temperature, lubricant flow rate, and bearing temperature. These variables and the bearing material properties dictate the performance of a bearing. It is important to test a material’s wear rate in all lubrication conditions – boundary, mixed and hydrodynamic – and, to gather data on all critical parameters. Based on the survey and critical parameters, a design matrix was developed for a bearing test bench capable of testing all conditions. A design was developed, evaluated, and constructed. The bearing test bench was subjected to validation and commissioning testing to demonstrate functionality. A baseline testing methodology was established, and testing protocols were developed to ensure the quality of data collected. Lubrication regimes were identified over a range of bearing surface speeds to select parameters for wear testing. Wear testing was then completed on bearing materials at pressures of 0.6 MPa and surface speeds of 2.16 m/s. The test bench produced reliable data on the wear rate for a given set of bearing parameters. Recommendations were then made regarding test protocols to better characterize wear performance of bearing materials.

Background Information:

A bearing is a device that supports a load while allowing movement in a desired direction or motion. Rotary bearings support radial loads while allowing free rotation of the shaft while holding its axis in a fixed position [1]. There are two major categories of rotary bearings: rolling and sliding bearings. This study investigates the latter.

Fluid film bearings are a type of plain bearing which uses a lubricant to produce a thin film that separates the bearing and journal surfaces [1] & [2]. If a suitably thick film is established, there is no contact between the journal and the bearing. Very low coefficients of friction are observed in this scenario.

Lubrication Modes

Within fluid film bearings there exists three major lubrication regimes: the hydrodynamic, mixed, and boundary lubrication regimes. In the hydrodynamic state, the thin film completely separates the two surfaces. There is essentially no wear as there is no contact between the surfaces. In the boundary state, the surface asperities of the journal and bearing contact each other and there are only small pockets of lubricant between the materials which do not carry any significant amount of load. A higher amount of wear occurs in this condition. Finally, in the mixed condition, there exist both areas where a fluid film is established and areas where the larger surface asperities of one material are in contact with the surface asperities of the other [1] & [2].

Hydrodynamic film is dependent on the relative speed and loading conditions. During starting and stopping, or when the unit is overloaded, the conditions for hydrodynamic film are not achieved. Therefore, the bearing can never operate in the hydrodynamic region for 100% of the time. Furthermore, if the operational parameters of the unit are not ideal, or if the unit is overloaded, the bearing may demonstrate a mixed or thin-film lubrication in which a slight, but continuous, wear will occur.

Water Lubricated Bearings

One option for the working fluid of a hydrodynamic film is water. The challenge of using water as opposed to traditional mineral oils is the much lower viscosity of water which reduces the potential film thickness. Oil spills have several negative and long-lasting effects on aquatic environments [3]. Using water eliminates the risk of oil contamination to waterways and can be supplied from the same source feeding the turbine.

Types of Materials Used in Water Lubricated Bearings

Several materials are currently utilized for water lubricated bearings. To mention a few there are PTFE composite bearings [4] & [5], rubber bearings [6], various polyurethane elastomer based bearings [7], [8], & [9], and wooden bearings.

Survey of Current Testing Methods

A survey of test standards and academic research pertaining to water lubricated bearings was conducted. Research was compiled for journal bearings subject to a continuous sliding motion in a single direction as this matches the operating conditions of water lubricated guide bearings used in the hydro electric industry. Wicket gate or other bearing applications that experience an oscillating motion were not considered in this study.

Testing Standards

Standards relevant to water lubricated bearings were surveyed. Block-on-ring testing that simulates a continuous sliding motion is most relevant to journal bearings used in hydro electric and marine industries. A diagram of the block-on-ring test method is shown in Figure 1. The terms block and ring are used within this paper refer to the bearing and shaft material respectively.

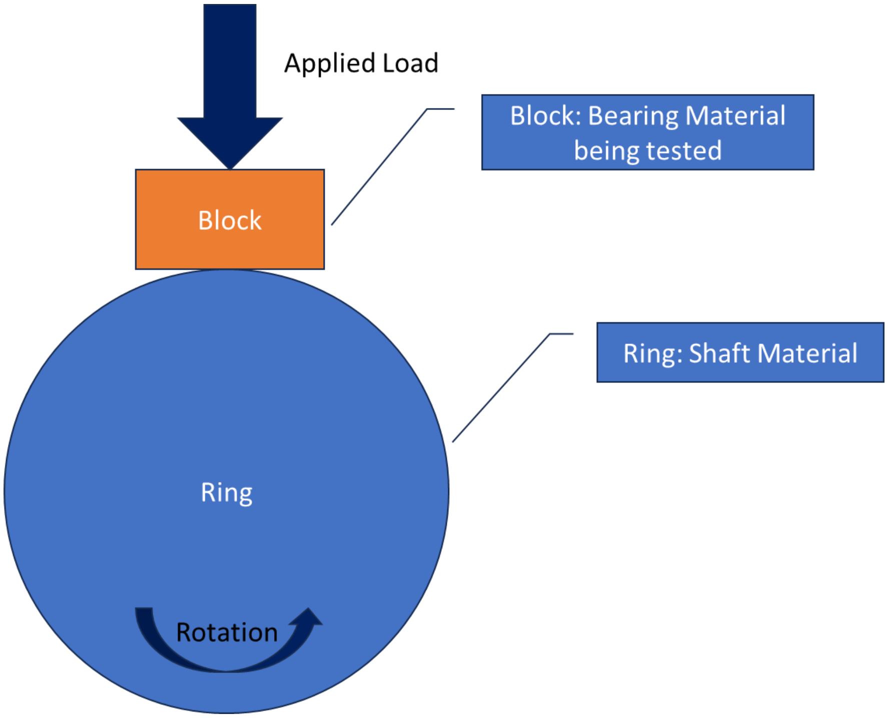


Figure 1: Image representing a block-on-ring test.

Of the standards surveyed, it was found that the following were applicable to water lubricated bearings:

- ASTM G77-17: Standard Test Method for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test [10],
- ASMT G176-03: Standard Test Method for Ranking Resistance of Plastics to Sliding Wear Using Block-on-Ring Wear Test – Cumulative Wear Method [11]
- MIL-B-17901B Amendment 3: Bearing Components, Bonded Synthetic Rubber, Water Lubricated [12] and
- DNV CP-0081: Synthetic Bearing Bush Materials [13]

Each standard emphasized the importance of replicating the tribological system that was under investigation. Guidance was also provided on the importance of using similar test durations to evaluate and assess materials. A comparison of the test standards is given in Table 1.

No clear pattern emerged in the requirements for speed and load conditions – the two most critical parameters that determine bearing life [1]. Usually, the standard suggested that the speed and load conditions be matched to the application in question. While this allows for a wear rate applicable to the exact condition in question, it makes a comparison between materials difficult, as testing at one lab may use a different set of conditions from another lab testing different materials. Furthermore, this complicates material choice for bearing designers as wear testing would have to be completed on a material for each speed-load combination it would be applied to. In practice, it is the shaft speeds and bearing loads of a unit that determine the bearing requirements – in other words, the bearing is designed according to the needs of the unit it will be installed in; the unit is not designed around the bearing. As such, a range of testing conditions must be completed for a given bearing material to understand its performance in a variety of applications.

Table 1: Comparison of wear tests used on water lubricated bearing materials.

Parameter	Test standard			
	ASTM G77	ASTM G176	DNV-CP-0081	MIL-B-17901B
Ring Surface Finish (initial)	0.15 to 0.3 µm (6 to 12 µin)		0.5 µm (~ 20 µin)	< 0.4 µm (< 16 µin)
Block Surface Finish (initial)	0.1 to 0.2 µm (4 to 8 µin)		0.5 µm (~20 µin)	< 1.6 µm (< 63 µin)
Ring Diameter	34.98 mm (1.377 inch)	34.99 mm (1.378 inch)	> 35 mm (> 1.378 inch)	54 mm (2.125 inch)
Bearing Length	6.35 mm (0.250 inch)		2w**	31.75 mm (1.25 inch)
Test Sample Geometry	15.75 x 10.16 x 6.35 mm (0.620 x 0.400 x .250 inch)		Dependent on bearing size	25 x 25 x 6.35 mm (1 x 1 x 0.25 inch)
Surface Speed	User defined *	0.37 m/s	6 m/s	0.27 m/s
Lubricant	Yes, as applicable	Not listed	Sea Water	Water with Abrasives Temp 75 F ± 5 F
Test Pressure	User defined	0.69 MPa	0.6 MPa	***
Test Distance/Time	User defined	20h (240 000 revs)	192 hours to 840 hours	10 hours
Starts/Stops	0	0	Every 8 hours	0
Replicates	As per ASTM E122			3

* Listed RPMs within standard yield a 0.13 to 0.36 m/s bearing surface speed
** Geometry of ring and block are given by a dimensional relationship defined within the standard
*** Standard gives contact load as 1.76 lbf –bearing land area required to determine pressure

Current Testing in Academia

Several researchers are conducting laboratory experiments on the wear rate and performance of various bearing materials with a focus on water lubricated bearings. Various test machines of both large-scale and small-scale testing have been constructed. Commercially available machines are also in use at laboratories that complete wear testing according to ASTM G77 & G176 [14]. Both the academic and commercial machines were surveyed and a summary of the testing capabilities is available in Table 2. It should be noted that this table may not reflect the full range of each machine’s capabilities, but it does represent the common speed load combinations applied by other researchers investigating water lubricated bearings.

Table 2: Survey of wear testing machines used in research of water lubricated bearings.

Parameter	Water Lubricated Testing Machines						
	FALEX [14]	Gdansk University of Technology [5], [6], [7], [8], [9], [15]*			Kobelco Eagle Marine Engineering [4]		Shanghai Jiao Tong University** [16]
Ring Diameter (mm)	34.98	100	100	65	200	300	80
Bearing Size (mm)	10.16 x 6.35	100 x 300	100 x 200	65 x L[†]	200 x 400	300 x 650	80 x 80
Shaft Speed (RPM)	60 to 3600	0 to 660	1000 to 3000	480	600	60	1500 to 4000
Surface Speed (m/s)	0.11 to 6.6	3.46	5.24 to 15.27	1.63	6.28	0.94	6.28 to 16.76
Lubricant	Water or Oil	Water	Water	Water with Debris	Water with Debris	Clean Water	Clean Water
Lubricant Temp. (C)	User Defined	Room Temp	Room Temp	Not listed	20 to 25	24 to 27	20
Test Pressure (MPa)	0.7 to 90	0.3 to 1.7	0.2 to 0.8	0.65	1	1.5	0.3 to 0.8
Test Duration	User defined	Not Listed	Not Listed	70 hours	1000 hours	4 months	Not Listed

* Some tests are related to wear while others are more focused on friction or film thickness
** This test rig was designed for testing water film thicknesses and coefficients of friction
[†] Length was not reported

Once again, there is a lack of consistency between testing set-ups, loads, speeds, and other conditions – even when testing across similar applications. This causes uncertainty in ranking and comparing bearing materials from these tests. Furthermore, some test results fail to publish sufficient information to reproduce or compare the result. Survey observations show that often the test duration is not reported; this is also problematic as wear can be non-linear and it is best to compare wear of materials subject to the same sliding distance or time tested. Finally, the material type tested is not always reported [7] & [17] and this makes it impossible for a bearing designer to apply the research to the design at hand. At a minimum, the scientific name of the materials should be given, for example Polytetrafluoroethylene (PTFE) could be listed as the material, as opposed to the tradename of Dupont's Teflon.

Survey of Water Lubricated Bearings in Use Within the Hydro Electric Industry

A brief survey of water lubricated bearings in hydroelectric stations was conducted. The results are found below in Table 3. Information on the bearing speed, load and geometry for the bearings was collected when available.

Table 3: Survey of water lubricated bearings used in hydro electric units.

Bearing Type	Diameter (mm)	Journal Length (mm)	Bearing Surface Speed (m/s)	Bearing Pressure (MPa)
Vertical Guide	355	890	2.57	0.31
Vertical Guide	455	1140	4.29	0.31
Vertical Guide	495	560	4.4	0.26
Horizontal Guide	295	487.5	3.48	-
Horizontal Guide	270	320	3.18	-
Horizontal Guide	245	462.5	2.89	-
Horizontal Guide	315	29.5	3.71	-
Horizontal Guide	196	305	1.85	-
Horizontal Guide Center Bearing	187	565	1.47	0.89
Horizontal Guide Headcover Bearing	187	450	1.47	0.84
Horizontal Guide	222	375	3.49	-

For vertical guide bearings, bearing pressure is typically around 0.3 MPa whereas a horizontal guide bearing, which also must aid in supporting the weight of the turbines and shafting, was much higher and typically around 0.9 MPa. Bearing surface speeds varied from 1.47 m/s to 4.4 m/s. Water temperature available to feed these bearings ranges from 1 C to 30 C.

Additional Parameters Required to Define a Test Method

Both the literature review and experience show that consideration must also be given to the number of start-stop events, duration of the testing, lubricant supply temperature, and lubricant flow rate. Additionally, a statistical evaluation must be completed to determine the number of test replicates required to provide the desired resolution.

There is considerable variation within these parameters between hydro electric units. For example, a pumped storage unit will experience far more start-stop events than a impoundment unit. Some test standards give direction on the number and frequency of start-stop cycles and most researchers in academia are controlling the lubricant temperature and flow rate. However, there is no clear standard or consistent reporting of these values within or across test facilities.

Evaluation Matrix for a Bearing Test Machine

Prior to designing the test bench, a requirements list was developed according to the literature review and surveys conducted. Design requirements were set after evaluating the three surveys. A matrix comparing machine requirements to the results of the surveys was constructed to document and identify machine requirements as shown in Table 4.

Table 4: Comparison of survey requirements and engineering requirements of bearing test bench design

Requirement	Survey			Design Requirement	Required Change	Design Options
	Test Standards	Academia	Hydro Electric			
Speed Control to Provide "X" m/s	6	1.6 to 17	1 to 5	0.4 to 6.5	Additional Controller	Manual/Auto Switch with Speed Control
Testing Load (MPa)	1.2	0.6	0.3 to 0.9	1.5	Upgrade Journals	New Collar Rims and Load Arm Designs
Estimated Torque for Load (ft-lbs)	15	7	13	20	5 HP Motor and Drive	5 hp 3 Phase Motor
Lubricant Temp (C)	20	20 to 30	1 to 30	20 to 80	Heat Exchanger & Heater	Upgrade Tubing to High Temp PEX
Friction Coefficient	Y	Y	Y	Y	Torque Sensor	-
Journal Materials & Hardness	SS 50 HRC	-	-	Modular Design	Stainless Steel and Bronze	Install as Required
Journal Materials - Finish	0.8 µm	-	-	<0.8 µm	Surface Roughness Ra - 0.8 µm	Machine as Required
Water Contaminant Conditions	Y	Y	Y	Y	Upgrade Steel to 316 SS	-
Add Contaminants to Lubricant	N	Y	Y	Y	Bypass to Operate Without Pump	Program PLC & Abrasive Pump System

It was decided to use the geometric relations listed in DNV-CP-0081 and use a fully conforming sample. As such, the block scar width and volume are not applicable as any uneven wear patterns would suggest the test result be rejected.

Each standard has different requirements on what test data and conditions must be reported. A comparison of the reporting requirements is listed below in Table 5. Based on the other surveys completed in this work, a list of reporting requirements for our testing has been developed and is also listed. Testing protocols and data collection sheets were developed to ensure that all required reporting data was collected by those conducting the testing.

Table 5: Reporting requirements of test standards vs Hydro Tech's testing methodology

Reporting Requirement	ASTM G77	ASTM G176	DNV-CP-0081	MIL-B17901B	Hydro Tech
Block Material	X	X	X	X	X
Block Hardness	X	X	X	X	X
Ring Material	X	X	X		X
Ring Hardness	X	X	X		X
Ring and Block Initial Surface Finish	X	X	X		X
Number of Replicates	X	X	X		X
Block Scar Width	X	X			N/A
Block Scar Volume	X	X			N/A
Ambient Conditions	X	X	X		X
Wear on Ring			X		X
Wear on Block	X	X	X	X	X
Wear vs Time (mm/hr)			X		X
Coefficient of Friction	X	X	X	X	X
Test Duration (hours)		X	X	X	X
Test Sliding Distance (m)		X			X
Block Temperature During Testing			X		X
Lubricant Temperature During Testing					X
Lubricant Flow Rate During Testing					X
Thickness in Wearing Direction Pre-test				X	X
Thickness in Wearing Direction Post-test				X	X
Diameter of Journal Pre-test				X	X
Diameter of Journal Post-test					X
Wear Pattern Observed	X	X			X
Initial and Final Mass of Block					X
Pre-test Pictures of Block and Ring					X
Post-test Pictures of Block and Ring					X

Differences in testing methods and calculations used to determine the wear rate of the material led to different reporting requirements. However, it is common that block material and hardness, total wear on the block, and coefficient of friction are reported. Caution is warranted in comparing tests of different durations [10], [11] & [18] as the wear rate can be non-linear for a given range of testing. A standard test duration will be required to rank and evaluate the wear of different bearing materials. Experience shows that bearing temperature is critical to understanding bearing material performance and it is surprising that only one standard (DNV-CP-0081) requires its recording and reporting.

Due to the ease of taking photos with smartphones and digital cameras, it is also recommended that pictures of the wear surface be reported before and after each test.

Design of the Bearing Test Bench

A bearing test bench capable of testing materials as per the geometry of DNV-CP-0081 wear test (See Figure 2) was designed and constructed. A 50 mm diameter ring was selected for use. The resulting bearing length was 42 mm long with a width of 21 mm.

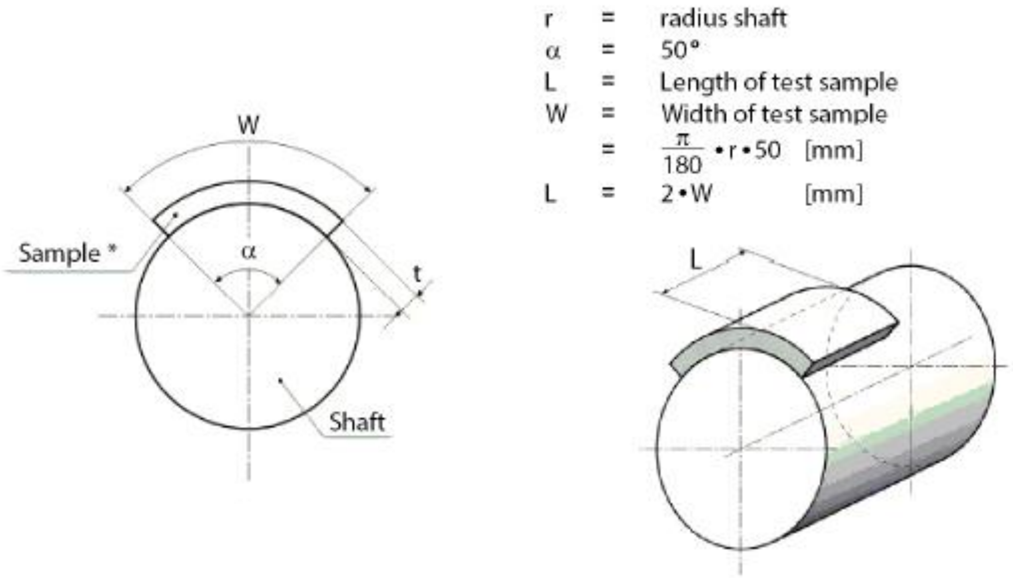


Figure 2: Geometric relationships used within DNV-CP-0081 [13].

The loading mechanism works with weights hung on the end of an arm. A load cell is mounted between the sample holder and test arms to continuously measure the applied load. As the weight moves down, the bearing sample is lifted into the 50 mm wear ring. The test bench can record the wear rate continuously throughout a test by using a position sensor integrated into the arm. The position sensor and bearing samples are mounted the same distance from the pivot point, allowing the position sensor to continuously measure the displacement of the bearing sample - and therefore thickness in the wear direction - during testing. A stop is integrated onto each arm so that the metallic bearing holder cannot collide with the wear ring. A schematic showing the loading mechanism is shown in Figure 3.

To measure torque and shaft speed, a torque sensor with built-in encoder is mounted via flexible couplings between the electric motor and driveshaft. The measured torque can be used to calculate the dynamic friction. A paddlewheel flow sensor is used to measure the lubricant flow rate during testing. The circulation pump can be set up to run in a closed or open loop system. The entire system is controlled by a programmable logic controller (PLC). Engineering controls have been built into the program to ensure that: all guarding is in place during operation; the machine will shut down in the event of an overload or shaft seizure; the machine will shut down if lubricant flow falls below the minimum set point; and, that the machine shuts down once the test time is complete or when the desired amount of wear has been reached.

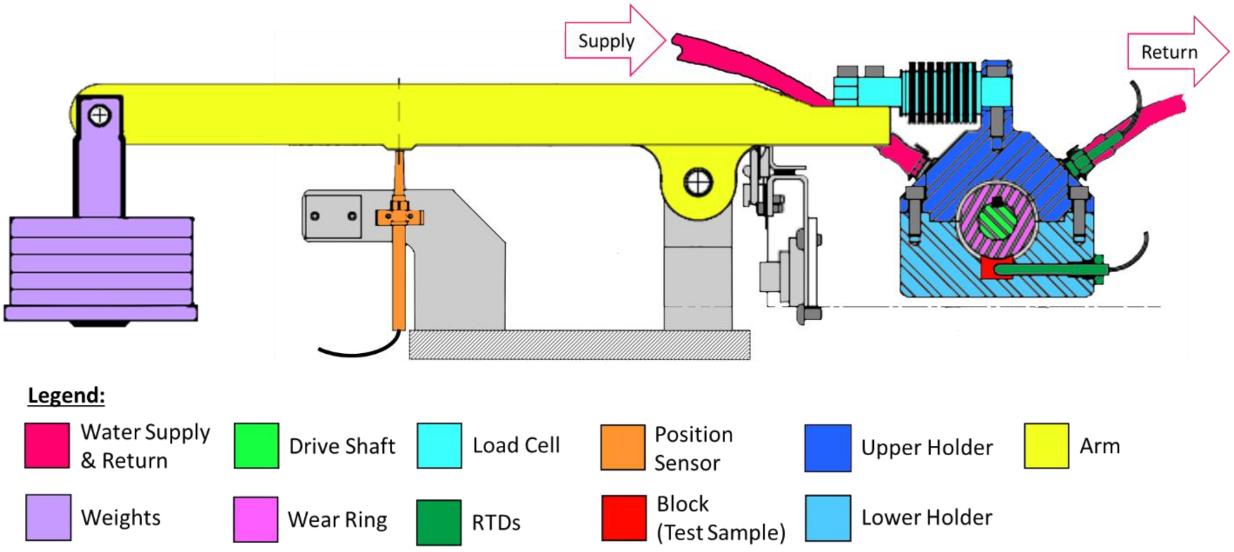


Figure 3: Cross section of bearing test bench showing loading mechanism.

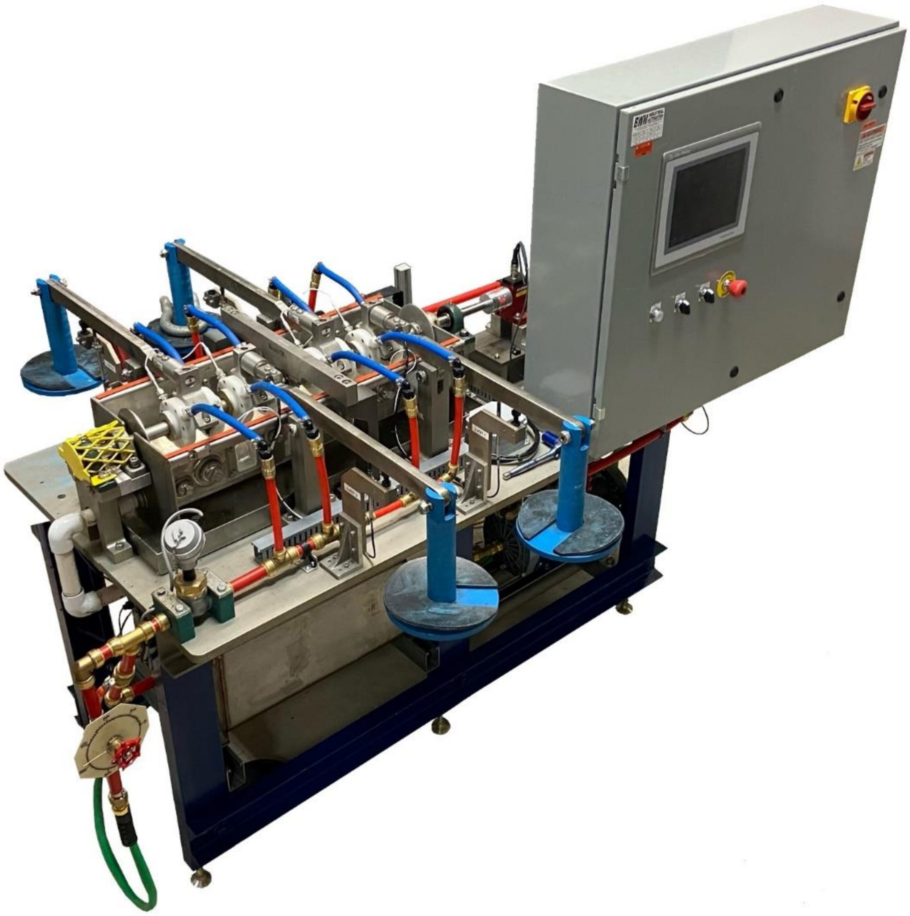


Figure 4: Image of the bearing test bench

The test bench is capable of testing four different bearing samples at one time. The integrated electric motor and drive allows the shaft speeds to be varied from 120 to 2500 rpm giving a bearing surface speed ranging from 0.32 m/s to 6.5 m/s. Weights are applied onto arms at a 2:1 lever and can apply a pressure of 0.2 MPa to 1.5 MPa on each bearing sample. A picture of the test bench is shown in Figure 4. The machine uses a heat exchanger to keep the lubricant (water) at a temperature of 23 C ± 3 C. The heat exchanger can be switched off and a heater can be submerged into the reservoir allowing for testing with lubricant temperatures from 30 C to 80 C. 3-wire platinum RTDs are used to monitor the bearing temperature, lubricant inlet temperature and outlet temperature. All data is recorded by the PLC into a spreadsheet and saved onto a secure digital card.

The bearing geometry utilized by DNV-CP-0081 is one in which the bearing (block) and shaft (ring) is fully conforming. (This geometry was previously shown in Figure 2). The bearing (block) does not have a leading edge. The diameter of the ring and block are identical meaning that there is no eccentricity introduced into the system. Due to this no wedge shape is formed between the rotating shaft and the bearing material which hinders the development of a hydro dynamic film. If the bearing geometry is changed to include a leading edge or a larger bore is applied to the bearing journal, a hydro dynamic film can be more readily established. The initial results presented in this paper utilize a block with the geometric relationships in DNV-CP-0081 using a 50 mm wear ring. The final dimensions of the block and ring are shown in Figure 5.

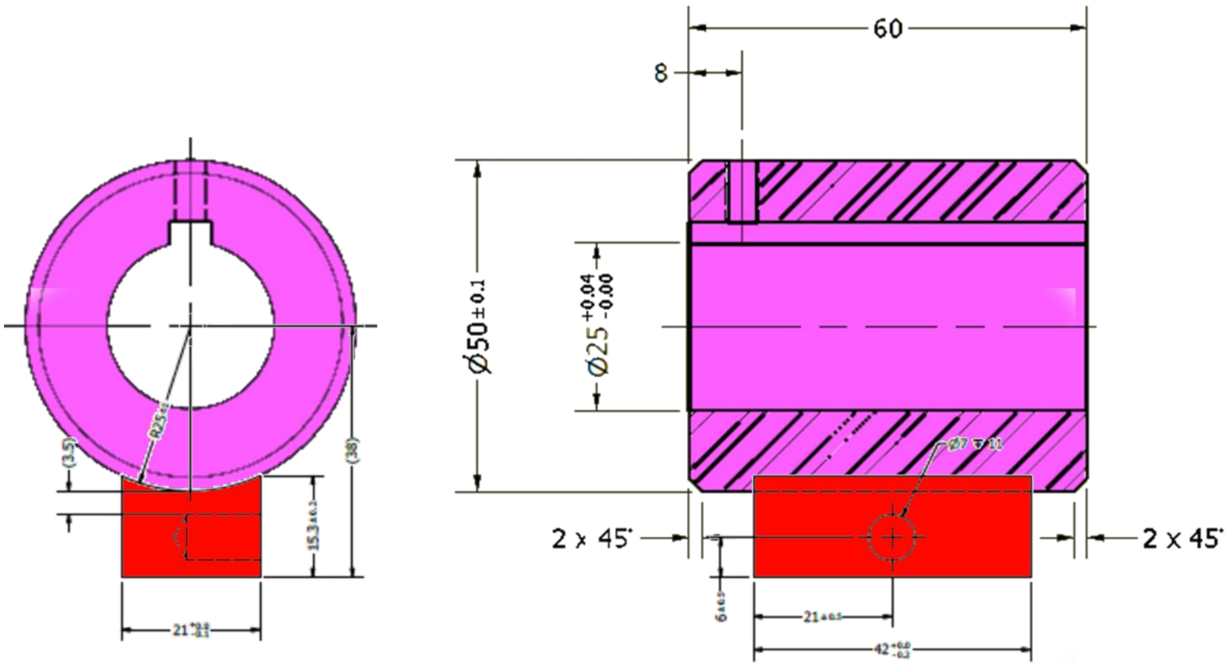


Figure 5: Image of fully conforming block and ring geometry

Construction and Validation of the Machine

The machine was built and assembled. Upon completion, the machine's shaft alignment and runout was evaluated. The shafts of the electric motor, torque sensor, and drive shaft were aligned within 0.001" of each other and connected via flexible couplings. The runout of the driveshaft was measured at each wear ring using a dial gauge capable of measuring to the nearest tenth of a thou. The runout was found to be less than 0.0003" at the wear collars.

Results and Discussion

After construction, testing was conducted on various bearing materials available. Through this initial testing, many observations were made regarding proper test procedures for bearing materials.

Preliminary Findings

The test bench was then used to examine the wear rate of various bearing materials. The objective of the initial testing was to gather baseline data that would allow us to develop a test procedure that would characterize the performance of a bearing material over a wide range of applications. A comparison can be made with vehicle mileage testing: The EPA approved fuel consumption for a vehicle may not exactly represent the mileage that an individual will experience, but does provide a method to rank and compare the fuel consumption of different motor vehicles for a set of given circumstances that is largely applicable to a high percentage (90%+) of users [19] & [20].

Ambient Conditions

Table 6 shows the range of testing conditions in which all research presented within this paper was conducted. No adverse conditions were identified.

Table 6: Laboratory Test Conditions

Test Condition	Range
Ambient Temperature	19 C ± 2 C
Room Humidity	20 to 45% RH
Lubricant Temperature	23 C ± 3 C
Lubricant Flow Rate	6.0 to 7.5 Litres per Minute
Lubricant Type	Tap Water (Fresh Water)
Supply Pressure	42 ± 1 PSI

Sample Preparation

For the preliminary testing, samples of Guaiacum officinale and polyurethane elastomer were machined according to DNV-CP-0081 requirements for a 50mm diameter journal. The surface finish of the bearings was 0.4 to 0.8 μm, while the journal material was machined to a 0.5 μm finish.

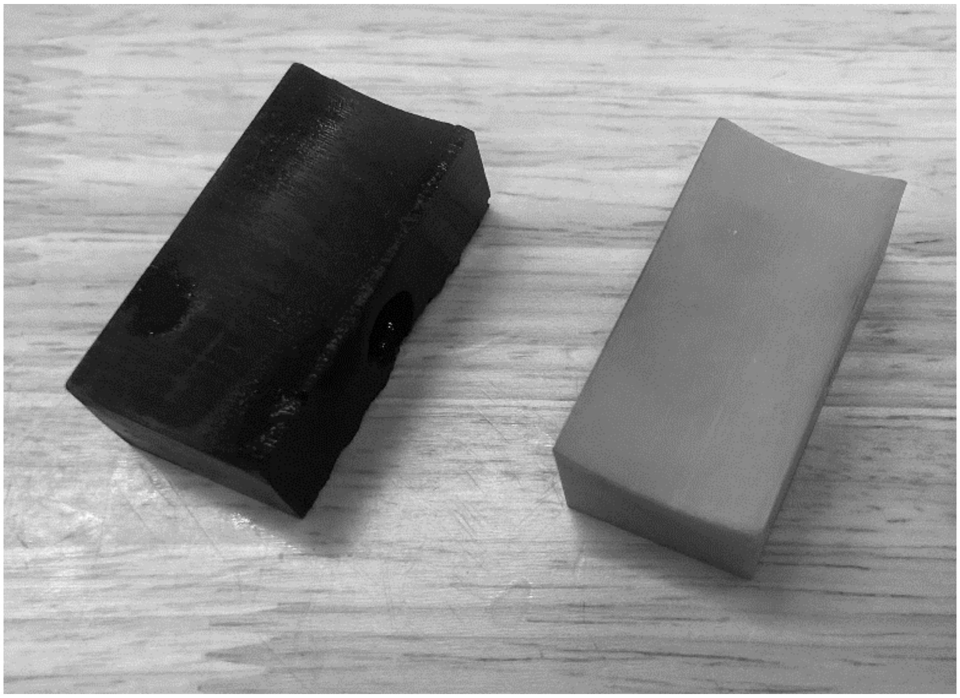


Figure 6: Image of Guaiacum officinale and polyurethane elastomer samples machined to size.

A go-no-go gauge was manufactured to check the bearing and journal surface conformity. The gauge also checks that the block's width, height, and thickness are within the specified tolerance. An image of the gauge is shown in Figure 7.

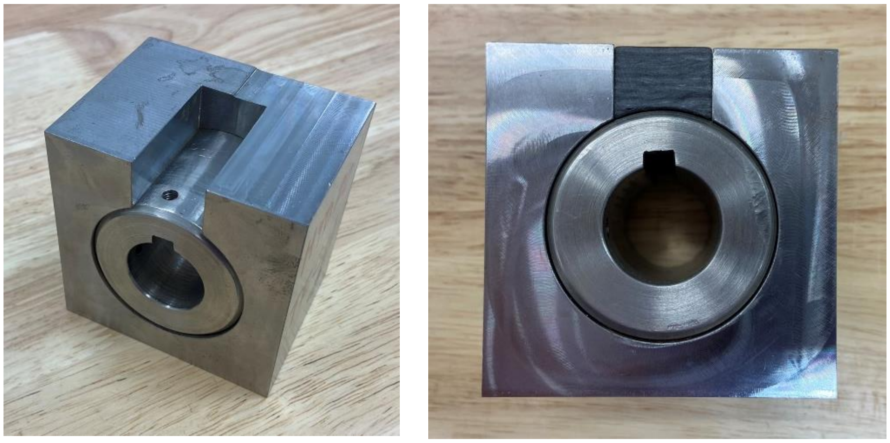


Figure 7: Image of Go-No-Go Gauge

Lubrication Regime Testing

By measuring the required torque, the lubrication regimes were identified across a range of bearing surface speeds using a constant load of 0.3 MPa. The speed was varied in small increments from 625 rpm (1.64 m/s) to 2500 rpm (6.54 m/s). The test was repeated twice for each bearing material to ensure that the results were repeatable.

For both materials it was observed that the torque reached a low point around 5 m/s with an increase in required torque as speed increased further. This indicates a transition into the hydrodynamic region as the increase in torque is explained by the increase in viscous friction with increasing bearing surface speed. The highest torque was observed at the slowest speed of 1.6 m/s. Back calculating the coefficient of friction from the applied load of 0.3 MPa gave a coefficient of friction of 0.2 for Guaiacum officinale. This correlates well to the coefficients of friction of 0.19 ± 0.03 as reported in the literature [21]. Therefore, at low speeds, the test bench operated in the boundary condition. The rapid decline in required torque from 1.6 m/s to 3.0 m/s supports the formation of mixed mode lubrication. Estimated ranges of each lubrication regime are shown in Figure 8.

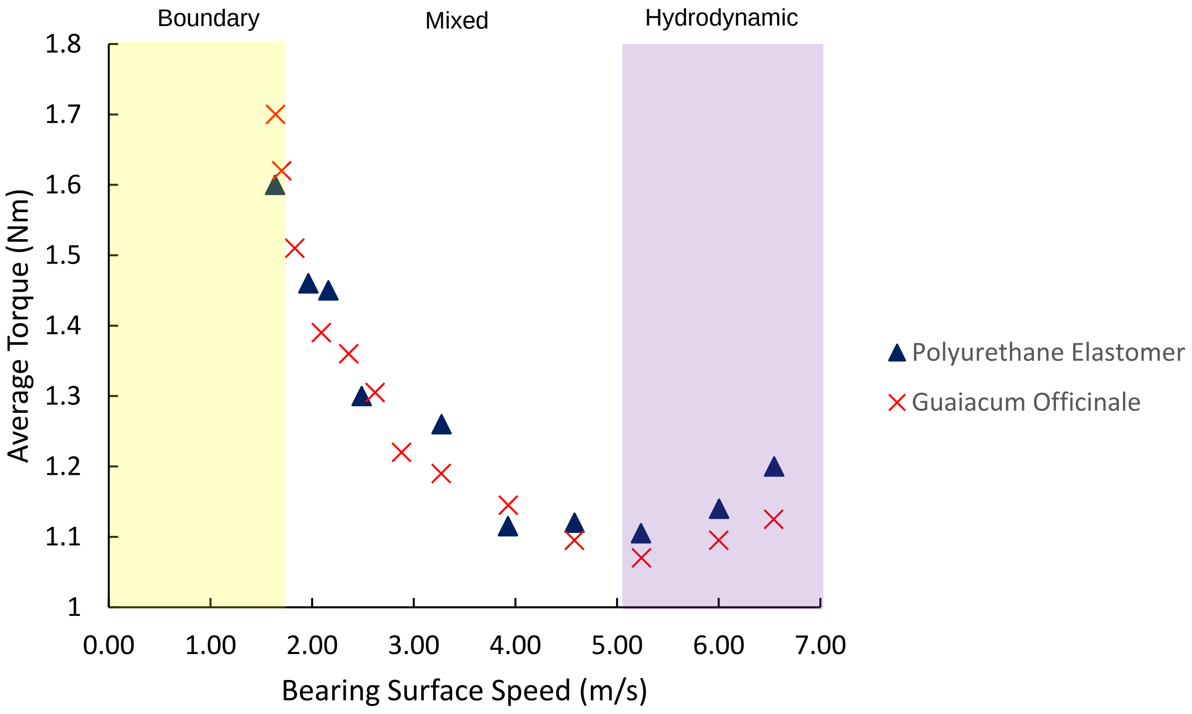


Figure 8: Drive Torque vs Bearing Surface Speed

Required Duration of Tests

A real challenge exists in testing these bearing materials due to their high resistance to wear. At the speed and load combinations currently being tested in academia, these bearing materials are expected to last 50 to 100 years. While it may be tempting to reduce the test duration to 20 or 40 hours so that testing can be conducted frequently and develop a larger sample size, sufficient time must be given to the test so that steady state behaviour is observed. Increasing the load and reducing the bearing surface speed would accelerate wear of the materials and thus reduce the required test duration. However, it is not straightforward how this accelerated wear rate would apply to the operating conditions the bearing material would be subject to.

To demonstrate the importance of test duration, a test was conducted in which bearing samples were subject to a 44-hour duration at 0.6MPa and 2.16m/s. Upon analysis of the wear rate, a high degree of variation was observed within the wear rate, as well as uneven wear patterns. The length of testing time was then increased until a uniform wear pattern was formed, and we observed that a 200-hour duration was the minimum test length that would give meaningful data. A comparison of the 44-hour and 200-hour test are shown below in Figure 9.

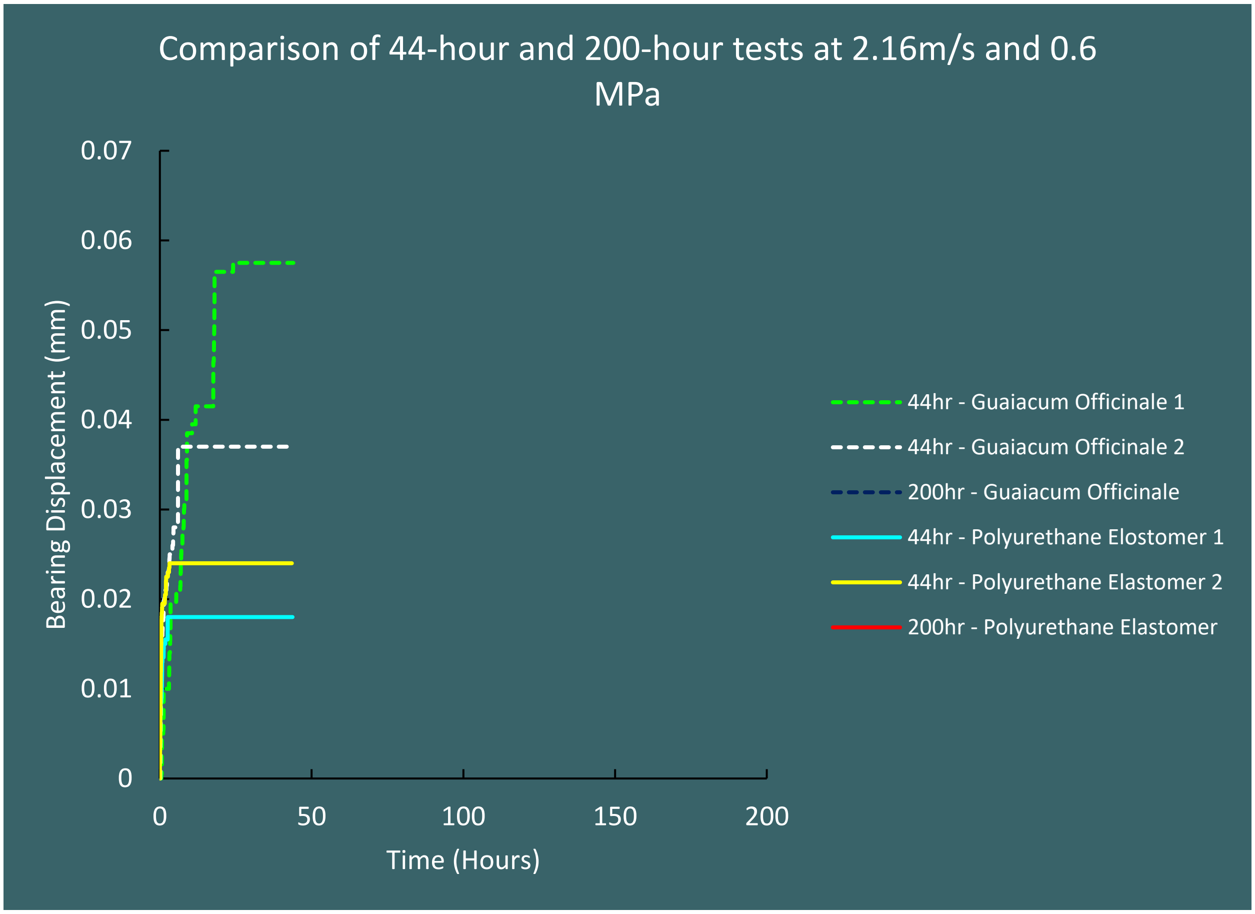
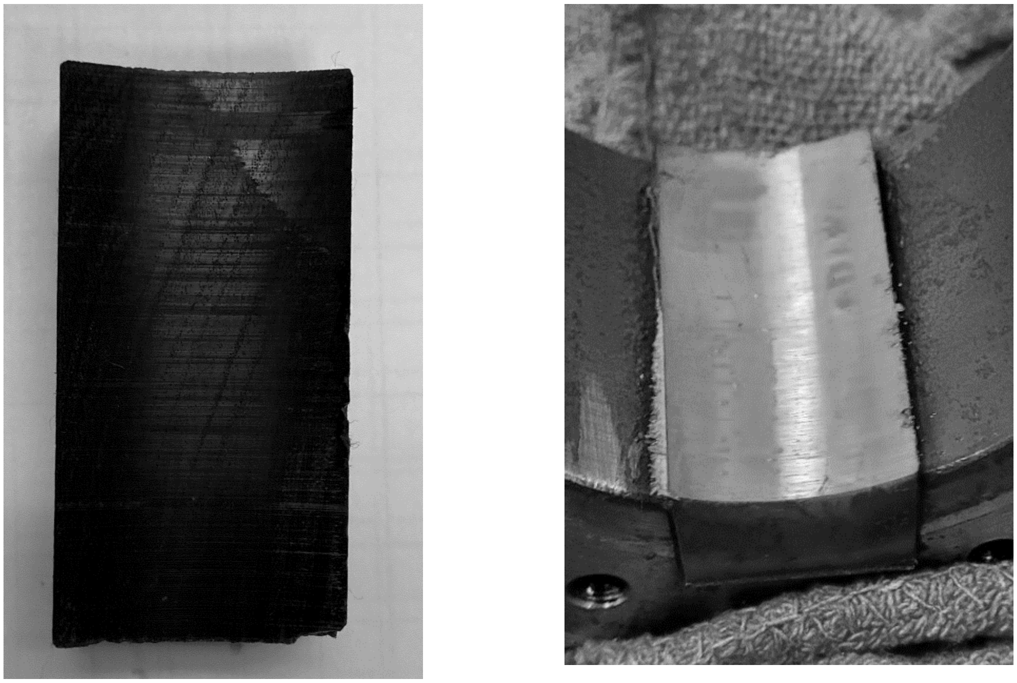


Figure 9: Comparison of 44- and 200-hour tests: dashed lines are Guaiacum officinale samples while solid lines are polyurethane elastomers.

In the 200-hour test, the polyurethane elastomer began to wear at a steady state after some time. It appears that the seating-in period required about 55 hours of testing for the plastic material. Once seated, the material began to wear at a constant rate as demonstrated by the slope of the bearing displacement over time. Contrastingly, the Guaiacum officinale demonstrated rapid wear during the first 25 hours of the test but then demonstrated almost no wear over the remainder of the test. It is speculated that differences in surface finish and machinability of the materials are responsible for the different wear rates during the initial seating, but further study and data is required to substantiate this claim. None the less, for testing performed near or at the operational conditions of a bearing material, the test duration must be longer than 200 hours.

This longevity complicates testing. For example, a single piece of wooden bearing material (21 mm x 42 mm) had not finished seating-in over a 200-hour period while operating in the boundary condition, see Figure 10.



Guaiacum Officinale (wood)

Polyurethane Elastomer (plastic)

Figure 10: Comparison of wear pattern after 200-hour duration test. Note top right corner of wood sample has not yet seated while the plastic sample has worn evenly over the whole surface.

All testing conducted under 44 hours would make it appear that Guaiacum officinale has a high wear rate. However, when the test duration was extended to 200 hours the opposite conclusion can be drawn. At this point it is important to state that not enough testing has yet been completed to draw conclusions and rank the performance of these two materials. What has been demonstrated is that a short test duration (less than 200 hours) will not provide adequate results to rank and compare bearing materials when testing bearing materials near normal loading conditions and bearing surface speeds.

Evaluation and Reporting of Wear Rate

It is proposed to evaluate the wear rate of the materials by three different methods. The first is to observe the average change in thickness through the wear direction. The second is to normalize the wear over the test duration. Finally, the third method calculates the volume of material in millimeters cubed lost per 1000 km (or one Mm) of sliding distance. Each method has benefits and limitations.

The first method is easy to complete, provided a micrometer with a one tenth (0.0001” or 2.5μm) resolution is used, but is only applicable to a single set of test parameters. The second method is easy to complete, provided the test duration is properly recorded, but cannot be compared to tests where a different bearing surface speed was used as a change in speed at the same duration will result in a change in sliding distance. The third method allows for comparison of wear rates across different speed combinations but requires testing at every load of interest. Additionally, the third method can be used to compare samples of different sizes as it considers the change in volume and not just the change in thickness. Lastly, all these methods are complicated by the non-linear behaviour of a wear test that results from the initial seating-in of the material.

The wear rates evaluated by each method are compared below for the two materials tested. The test parameters used are a constant load of 0.6 MPa and 2.16 m/s. Only a single replicate of the testing has been completed and no meaningful conclusions can yet be made to rank the materials' performance against each other. The initial results are listed in Table 7.

Table 7: Comparison of the wear rates calculated by the three proposed methods using measurements from the 200-hour test.

Material	Method 1 (µm)	Method 2 (µm/hr)	Method 3 (mm^3/Mm)
Guaiacum Officinale	90	0.45	1.27
Polyurethane Elastomer	108	0.54	1.52

Conclusions

1. A test bench which is capable of bearing surface speeds of 1 m/s to 6 m/s is adequate to test water lubricated bearing materials for use in hydro electric applications and will demonstrate the expected lubrication regimes.
2. A test bench capable of applying 0.2 to 1.5 MPa bearing surface pressure is adequate for testing water lubricated bearing materials for use in hydro electric applications.
3. The test duration has a significant effect on the results and test durations less than 200 hours should be avoided due to the non-linear seating in period that occurs at the beginning of the test.

Recommendations for Future Study

The following recommendations regarding this work have been put forward for consideration:

1. Continue testing various materials with the bearing test bench to determine the effects of different speed-load combinations, start-stop events, lubricant temperatures, lubricant contaminants, and lubricant flow rates on a material's wear rate.
2. Examine the effect of machinability, initial surface finish, and surface topology on the initial wear rate of both guaiacum officinale and polyurethane elastomers.
3. Increase the number of sample observations in the survey of hydro electric units to establish a higher confidence that our survey has a population which

accurately reflects the industry’s needs. Also, observe the number of start-stop events, water quality, overspeed conditions, and journal surface finishes of each hydro electric unit.

4. Complete a survey of sediment and debris commonly found in river water.
5. Develop a test protocol which tests several speed load combinations, start-stop events, lubricant temperatures, an overspeed condition, and water contaminants that represent a high percentage of water lubricated bearings and allows for different bearing materials to be ranked according to their wear performance in a direct comparison.
6. Investigate and analyze the different wear rate calculations at varied loads and bearing surface speeds and determine which method of wear rate reporting best applies to water lubricated bearings.

Acknowledgements:

I would like to thank Marty Sdao, Michael Paciocco, Ariful Islam and Sean Whelan-Marcolini for their assistance in completing this work. Michael and Sean were instrumental in the test bench’s design and commissioning. Ariful and Marty have helped immensely in keeping the test bench running when I have been away. Marty has also assisted in continuously improving our testing protocols and data collection methods. I couldn’t ask for a better team to work with on this challenging but rewarding task. I would also like to thank Mike Dupuis for financially supporting this work and enabling us to build the machine we need.

Biographical Sketch:

Daniel Westerbaan has experience in testing and research methods gained while working at government labs (Argonne National Labs), universities (University of Waterloo), and research and development departments (Magna Advanced Technologies), as well as involvement in new program developments for aerospace OEMs during the initial production of the Bombardier Global 7500 business jet. Daniel is currently leading the research and development team at Hydro Tech to develop technologies and testing methods for the hydroelectric industry.

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